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3.5 keV X-ray line signal from decay of right-handed neutrino due to transition magnetic moment

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Abstract: We consider the dark matter model with radiative neutrino mass generation where the Standard Model is extended with three right-handed singlet neutrinos (N_1, N_2 and N_3) and one additional $SU(2)_L$ doublet scalar η. One of the right-handed neutrinos (N_1), being lightest among them, is a leptophilic fermionic dark matter candidate whose stability is ensured by the imposed $\mathbb{Z}_2$ symmetry on this model. The second lightest right-handed neutrino (N_2) is assumed to be nearly degenerated in mass with the lightest one enhancing the co-annihilation between them. The effective interaction term among the lightest, second lightest right-handed neutrinos and photon containing transition magnetic moment is responsible for the decay of heavier right-handed neutrino to the lightest one and a photon ($N_2 \to N_1 + \gamma$). This radiative decay of heavier right-handed neutrino with charged scalar and leptons in internal lines could explain the X-ray line signal ~ 3.5 keV recently claimed by XMM-Newton X-ray observatory from different galaxy clusters and Andromeda galaxy (M31). The value of the transition magnetic moment is computed and found to be several orders of magnitude below the current reach of various direct dark matter searches. The other parameter space in this framework in the light of the observed signal is further investigated.

Keywords: Neutrino Physics, Beyond Standard Model, Cosmology of Theories beyond the SM

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JHEP03(2015)064

Contents

JHEP03(2015)064

1 Introduction

One of the enigmas of modern particle physics is dark matter (DM) which, according to the recent survey of PLANCK [1], consists of $\sim 26.8\%$ of the total energy content of the universe. Various astrophysical and cosmological observations [2–4] strongly suggest convincing hints of the existence of DM which is non-relativistic or cold in nature. The particle nature of DM is still unknown. The weakly interacting massive particles (WIMPs) are the most promising candidates for cold DM.

The experimental techniques for the detection of DM for both direct and indirect cases are very challenging. In direct detection experiments, the recoil energy of the target nucleus scattered off by DM particle is measured whereas the signatures of the annihilations or decays of DM particles such as charged particles, photons and neutrinos etc. are aimed to detect in indirect searches. The feature of monochromatic line from such decay or annihilation of DM is particularly significant in predicting the nature of DM particles. A huge variety of DM models in the framework of WIMP scenario with masses of DM spanning from keV to TeVs has been addressed in several literatures and their direct and indirect detection prospects have been widely studied [5–18].

Recently an evidence of X-ray line of energy 3.55 keV with more than 3σ CL has been reported from the analysis of X-ray data of 73 galaxy clusters from XMM-Newton observatory [19]. Another group has also claimed a similar line (3.52 keV X-ray line at 4.4σ CL) from the data of X-ray spectra of Andromeda galaxy (M31) and Perseus cluster [20]. The galaxy clusters are assumed to contain huge amount of DM. Thus the signal may have a possible origin related to DM. The observed line has been explained as decay of sterile neutrino DM ($\nu_s \to \nu + \gamma$) with mass of the sterile neutrino being 7.06 ± 0.05 keV and mixing angle $\sin^2(2\theta) = (2.2 - 20) \times 10^{-11}$ [20]. Recently many other interesting ideas have been proposed to explain this line signal to come from DM [21–43].

The neutrino oscillation data [44–47] provide strong evidences for neutrino mass. The non-zero neutrino masses and evidences of DM give hints to the physics beyond the Standard Model (SM). The two beyond SM phenomena, namely the origin of neutrino masses and the existence of cold DM may have a connection. In this work we focus on the simplest

Particle	$N_k \, (k = 1, 2, 3)$	η
$(\mathrm{SU}(2)_L, \mathrm{U}(1)_Y)$	$(\mathbf{1}, 0)$	$(\mathbf{2}, 1/2)$
$\mathbb{Z}_2$	odd (-)	odd (-)

Table 1. Additional fields under SM gauge group and $\mathbb{Z}_2$ symmetry.

framework which invokes this idea of connecting both sectors and has been proposed by Ma [48]. In this model the neutrino masses are generated via radiative processes with only the DM particles in the loop. The right-handed neutrino which can be a possible DM candidate interacts with lepton doublets and hence DM in this scenario is leptophilic in nature. The imposed discrete $\mathbb{Z}_2$ symmetry on this model not only forbids the tree-level Dirac mass terms but also assures a stable cold DM candidate. Phenomenological prospects for collider and DM in this model have been done in refs. [49–58]. In this paper we consider the case where the lightest right-handed neutrino (N_1) is the cold DM candidate and the second lightest right-handed neutrino (N_2) is nearly degenerated in mass with the cold DM candidate. This situation provides rich phenomenology in direct detection of such DM candidate [60]. Elastic scattering cross-section for DM-nucleon interaction is suppressed in this case and inelastic scattering that occurs radiatively dominates. The transition from N_2 to N_1 gives rise to monochromatic photon with energy equal to the mass difference between the lightest and second lightest right-handed neutrinos. If the mass difference between N_2 and N_1 is of $\sim$ keV, then the recent observation of X-ray line can be accommodated in this beyond SM scenario.

The paper is organised as follows. In section 2 the theoretical framework of the model is briefly discussed. Explanation of the observed X-ray line in this model framework and a study of the constrained parameter space are done in the following section (section 3). In section 4 a brief summery of this work and some important conclusions are drawn.

2 The model

We consider the model proposed by Ma [48] which is the extension of Standard Model with three gauge singlet right-handed neutrinos N_1, N_2, N_3 and extra $\mathrm{SU}(2)_L$ doublet scalar η. The fields can be written as,

$$N_1, \quad N_2, \quad N_3, \quad \eta = \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix}. \tag{2.1}$$

The doublet scalar η is assumed to obtain no vacuum expectation value and hence inert. An additional discrete $\mathbb{Z}_2$ symmetry is imposed on the model. The stability of the cold DM candidate in this model is guaranteed by this symmetry. Not only that, the tree-level Dirac masses of neutrinos are forbidden for this additional $\mathbb{Z}_2$ symmetry. SM gauge group and $\mathbb{Z}_2$ charges of the particles are shown in table 1.

JHEP03(2015)064

The Lagrangian for the right-handed neutrinos, N_k $(k = 1, 2, 3)$ invariant under both SM gauge symmetry and $\mathbb{Z}_2$ symmetry can be written as,

$$\mathcal{L}_N = \overline{N_i} i \partial\!\!\!/ P_R N_i + (D_\mu \eta)^\dagger (D^\mu \eta) - \frac{M_i}{2} \overline{N_i{}^c} P_R N_i + h_{\alpha i} \overline{\ell_\alpha} \eta^\dagger P_R N_i + \text{h.c.}, \tag{2.2}$$

where $h_{\alpha k}$, ℓ_α and M_k represent Yukawa couplings, lepton doublet and the mass of the right-handed neutrino of type k (N_k) respectively. In our following work M_ks are chosen to be real without any loss of generality. The invariant scalar potential containing the Higgs doublet ϕ and the additional $\mathrm{SU}(2)_L$ doublet η is given by,

$$\begin{aligned}\mathcal{V}(\phi, \eta) = & \; m_\phi^2 \phi^\dagger \phi + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2} \left(\phi^\dagger \phi\right)^2 + \frac{\lambda_2}{2} \left(\eta^\dagger \eta\right)^2 \\ & + \lambda_3 \left(\phi^\dagger \phi\right) \left(\eta^\dagger \eta\right) + \lambda_4 \left(\phi^\dagger \eta\right) \left(\eta^\dagger \phi\right) + \frac{\lambda_5}{2} \left(\phi^\dagger \eta\right)^2 + \text{h.c.}.\end{aligned} \tag{2.3}$$

The tree-level Dirac mass terms for neutrinos cannot be generated since the vacuum expectation value of the doublet η $(\langle \eta \rangle)$ is chosen be zero. After electroweak symmetry breaking SM Higgs doublet obtains vacuum expectation value, $v = 246\,\text{GeV}$ and the Majorana masses of neutrinos are generated radiatively via one-loop diagrams with η^0 and N_k in internal lines. The model could explain both possibility of scalar (η^0) and fermion (N_k) as DM. But we choose the mass of one of the three right-handed neutrinos (N_1) to be lightest among the particles added to SM and hence it is a stable candidate of DM. From the forth term of the Lagrangian in eq. (2.2) it is clear that the right-handed neutrino interacts only with the SM lepton doublet and hence leptophilic.

The radiatively generated effective Majorana neutrino masses can be expressed as [48],

$$(m_\nu)_{\alpha\beta} \simeq \sum_{i=1}^{3} \frac{2\lambda_5 h_{\alpha i} h_{\beta i} v^2}{(4\pi)^2 M_i} I\left(\frac{M_i^2}{M_\eta^2}\right), \tag{2.4}$$

where $M_\eta^2 \simeq m_\eta^2 + (\lambda_3 + \lambda_4) v^2/2$, M_i are the masses of η and N_i respectively.[1] The smallness of the mass term is guaranteed by the coupling λ_5. The factor $I(x)$ can be written as,

$$I(x) = \frac{x}{1-x}\left(1 + \frac{x \log x}{1-x}\right). \tag{2.5}$$

Assuming the mass matrix of eq. (2.4) to be diagonalised using the PMNS matrix,

$$U = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\frac{\sin\theta}{\sqrt{2}} & \frac{\cos\theta}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{\sin\theta}{\sqrt{2}} & -\frac{\cos\theta}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \quad (\theta \text{ being the mixing angle}), \tag{2.6}$$

[1] Masses of the real and imaginary parts of η^0 and $\eta^\pm$ are taken to be degenerate for simplicity.

which provides very well explanation for the neutrino oscillation data, one can find some diagonalization conditions imposed on $h_{\alpha i}$ as [51],

$$\sum_{k=1}^{3}\left(2h_{ek}^2\sin 2\theta + 2\sqrt{2}h_{ek}(h_{\mu k}-h_{\tau k})\cos 2\theta - (h_{\tau k}-h_{\mu k})^2\sin 2\theta\right) = 0,$$
$$\sum_{k=1}^{3} h_{ek}\left(h_{\mu k}+h_{\tau k}\right) = 0, \qquad \sum_{k=1}^{3}\left(h_{\mu k}-h_{\tau k}\right)\left(h_{\mu k}+h_{\tau k}\right) = 0. \tag{2.7}$$

One of the simple solutions for these conditions on $h_{\alpha i}$ (eq. (2.7)) is achieved by choosing the flavour structure of $h_{\alpha i}$ as,

$$h_{ei} = 0, \quad h_{\mu i} = h_{\tau i}; \quad h_{ej} \neq 0, \quad h_{\mu j} = -h_{\tau j} \ \ (i \neq j)\,. \tag{2.8}$$

Thus either i or j takes any two values of k (1,2,3). In matrix notation the structure of the chosen Yukawa couplings of eq. (2.8) can be written as,

$$h_{\alpha i} = \begin{pmatrix} 0 & 0 & h'_3 \\ h_1 & h_2 & h_3 \\ h_1 & h_2 & -h_3 \end{pmatrix}. \tag{2.9}$$

The Yukawa couplings of eq. (2.9) imply the values of θ_{12}, θ_{23} and θ_{13} to be $\tan^{-1}(\frac{h'_3}{\sqrt{2}h_3})$, $\pi/4$ and 0 respectively. But recent observations suggest different values of these mixing angles. Then the structure of the matrix will be slightly modified [56–58]. The result of this work will not be vastly modified due to such changes.

A rough estimate for the thermal production of the DM relic abundance can be made in the present framework. The right-handed neutrinos in this model can, in principle, be produced in the early universe via different mechanisms. The productions of both N_1 and N_2 in the early universe are assumed to be similar. Since the mass of N_2 is slightly heavier than that of N_1 in this model, there will be the decay channels from $N_2 \to N_1$. The decay mode such as $N_2 \to N_1 + \nu + \bar{\nu}$ is also present other than $N_2 \to N_1 + \gamma$ process. The amplitude and decay rate for this process have been calculated using the derived formulation of ref. [58]. This decay process which is mediated by neutral scalars of η shows a dependency of forth power of Yukawa coupling on its decay width. The Yukawa coupling is also needed to be small to suppress the transition. Thus the production of DM relic abundance which is dependent on the Yukawa coupling should have been affected. But the co-annihilation effect between the two lightest fermions N_1 and N_2 which are very degenerate in mass leads to an effective enhanced annihilation cross-section [59] written as $\langle\sigma v\rangle_{\rm eff} = a_{\rm eff} + b_{\rm eff}v^2 + \mathcal{O}(v^4)$ with

$$a_{\rm eff} = \frac{\xi^2}{2\pi}\frac{M_1^2}{\left(M_\eta^2+M_1^2\right)^2}, \tag{2.10}$$
$$b_{\rm eff} = \frac{|h_1^2+h_2^2|^2}{24\pi}\frac{M_1^2\left(M_\eta^4+M_1^4\right)}{\left(M_\eta^2+M_1^2\right)^4} + \frac{\xi^2}{2\pi}\frac{M_1^2\left(M_\eta^4-3M_\eta^2M_1^2-M_1^4\right)}{\left(M_\eta^2+M_1^2\right)^4}, \tag{2.11}$$

where ξ is the phase difference between the Yukawa couplings h_1 and h_2. In the above, the terms proportional to ξ^2 come from $N_1 - N_2$ co-annihilation effect. In eq. (2.11) the terms proportional to the square of the Yukawa couplings, h_1^2 and h_2^2 are due to $N_1 - N_1$ and $N_2 - N_2$ annihilations respectively. Thus a_{eff}-term in eq. (2.10) which is responsible for s-wave is solely dependent on the co-annihilation effect. Hence it is possible to produce correct DM relic density by thermal production although the Yukawa coupling is very small. In addition to $N_1 - N_2$ co-annihilation, the co-annihilation of N_1 with inert doublet η also plays an important role in obtaining correct DM relic abundance. Hence for very small or negligible ξ, the contribution from $N_1 - \eta$ co-annihilation also helps to produce proper DM relic density. Thus suitable DM relic density set by the thermal production can always be obtained in this framework by the collective contributions from both the co-annihilations, $N_1 - N_2$ and $N_1 - \eta$ [60]. We have calculated the lifetime for the process $N_2 \to N_1 + \nu + \bar{\nu}$ ($\tau_{N_2 \to N_1 \nu\bar{\nu}}$) for several regions of the parameter space of this model where the lifetime for this decay process exceeds the age of the universe ($\tau_{\text{Univ}} = 4.36 \times 10^{17}$ s) even if there is no phase ξ. The calculated value of $\tau_{N_2 \to N_1 \nu\bar{\nu}}$ can be found to be within few times more than τ_{Univ} for these chosen regions of the parameter space in this framework.

The order of the neutrino masses has been computed for different zones of the allowed parameter space and is seen to be compatible with the known order of neutrino masses. A very recent fit of global data of neutrino oscillations [61] suggests that

$$\begin{aligned} \delta m^2 &= m_2^2 - m_1^2 = \left(7.54^{+0.26}_{-0.22}\right) \times 10^{-5}\ \text{eV}^2\,, \\ \Delta m^2 &= m_3^2 - \tfrac{1}{2}\left(m_1^2 + m_2^2\right) = \left(2.43^{+0.06}_{-0.06}\right) \times 10^{-3}\ \text{eV}^2\,. \end{aligned} \tag{2.12}$$

Various bounds from cosmological data such as the Planck Collaboration give the sum total value of all neutrino masses, $\Sigma_k m_k < 0.18 - 0.23\,\text{eV}$ [1, 62]. Other cosmological observations, however, hint larger values of $\Sigma_k m_k$ to be ~ 0.2 - 0.4 eV [63, 64]. The neutrino mass eigenvalues for the chosen structure of Yukawa couplings of eq. (2.8) in this model are simply written as,

$$\begin{aligned} m_1 &= \left(h_{ej}\cos\theta + \sqrt{2}h_{\tau j}\sin\theta\right)^2 \Lambda_j = 0, \\ m_2 &= \left(h_{ej}\sin\theta - \sqrt{2}h_{\tau j}\cos\theta\right)^2 \Lambda_j = \frac{2h_{\tau j}^2}{\cos^2\theta}\Lambda_j, \\ m_3 &= 2h_{\tau i}^2 \Lambda_i, \end{aligned} \tag{2.13}$$

where $\Lambda_i \equiv \frac{2\lambda_5 v^2}{(4\pi)^2 M_i} I\left(\frac{M_i^2}{M_\eta^2}\right)$ and there is summation over i and j. The results of neutrino masses for various points of the parameter space in this model are calculated and found to be compatible with both the abovementioned bounds.

3 X-ray line in this framework

One of the terms in the Lagrangian of this framework that represents the interaction among the lightest right-handed neutrino (N_1), second lightest right-handed neutrino (N_2) and photon is given by [60],

$$\mathcal{L} = i\left(\frac{\mu_{12}}{2}\right)\overline{N_2}\sigma^{\mu\nu}N_1 F_{\mu\nu}\ , \tag{3.1}$$

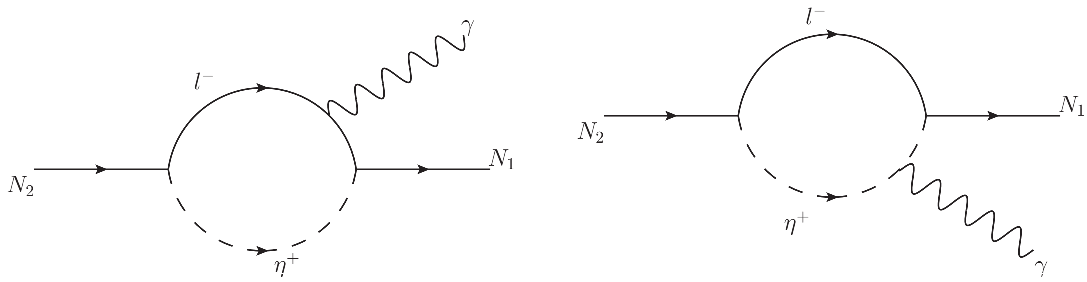

Figure 1. Feynman diagrams showing the decay of second lightest right-handed neutrino, N_2 to lightest right-handed neutrino, N_1 and photon (γ) via radiative processes.

where μ_{12} is the coefficient of this interaction and called *transition magnetic moment* between the right-handed neutrinos, N_1 and N_2. In the above $F_{\mu\nu}$ is the so-called electromagnetic field tensor. The three-point vertex interaction term of this type is also responsible in contributing to the inelastic scattering of the right-handed neutrinos with nucleons via 1-loop processes.

The X-ray line appears when there is a transition from the state, N_2 to N_1. The presence of transition magnetic moment solely triggers such a decay process to occur. The expression of decay width for this process can be written as,

$$\Gamma(N_2 \to N_1\gamma) = \frac{\mu_{12}^2}{\pi}\delta^3 \ , \tag{3.2}$$

where $\delta(= E_\gamma)$ is the energy of the emitted photon which is nothing but the mass difference between the lightest and the second lightest right-handed neutrinos present in this framework. The Feynman diagrams responsible for such process are shown in figure 1.

The calculated value of the decay width for the decay process of N_2 to N_1 and a photon from the observed X-ray line data is $\sim 1.15 \times 10^{-52}$ GeV [40]. Thus one can find from eq. (3.2) that to comply the observed data for X-ray line with the framework of this model, the absolute value of μ_{12} should be $\sim 2.9 \times 10^{-18}\,\text{GeV}^{-1}$.

The order of the value of $|\mu_{12}|$ is particularly important for studying the prospects of the direct detection of DM. The predicted value of $|\mu_{12}|$ from the recently reported X-ray line data is several orders of magnitude below the current reach of various DM direct detection experiments [60]. As the mass of the lightest right-handed neutrino DM in this model is heavy, possibly in the range from few hundreds of GeV to few thousands of GeV, the direct DM searches should probe these massive right-handed neutrinos in this mass range.

The expression for μ_{12} in the present scenario can be written in terms of model parameters [60] as,

$$\mu_{12} = -\sum_\alpha \frac{\text{Im}\,(h^*_{\alpha 2}h_{\alpha 1})\,e}{2(4\pi)^2 M_\eta^2} 2M_1 I_{\text{m}}\left(\frac{M_1^2}{M_\eta^2}, \frac{m_\alpha^2}{M_\eta^2}\right), \tag{3.3}$$

where m_α is the mass of charged lepton of flavour α, e is the electric charge of proton. The term $\text{Im}\,(h^*_{\alpha 2}h_{\alpha 1})$ in eq. (3.3) is related to the phase difference, ξ between the Yukawa

JHEP03(2015)064

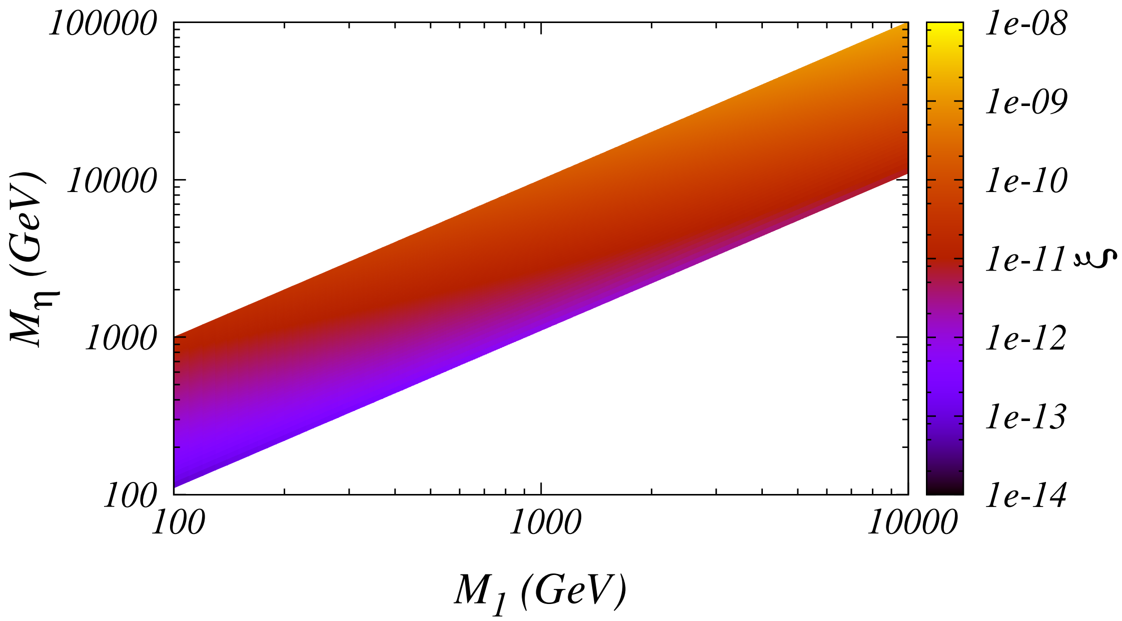

Figure 2. The allowed parameter space consisting of M_1, M_η and ξ consistent with the recently reported 3.5 keV X-ray line data. The value of ratio of the mass of N_1 to that of η is chosen to be within 10.0, i.e., $1.0 < M_\eta/M_1 \leq 10.0$ in this plot. The considered range of M_1 is from 10^2 GeV to 10^4 GeV. The phase factor ξ are shown by the colour index where ξ varies from blue coloured region to yellow region as its value increases. See text for more details.

couplings $h_{\alpha 2}$ and $h_{\alpha 1}$ for flavour α. For the matrix of Yukawa couplings of eq. (2.9) the value of the factor, $\mathrm{Im}\,(h^*_{\alpha 2} h_{\alpha 1})$ is zero for one flavour and contributes equally for the remaining flavours. In the above the function I_{m} comes from loop integration and can be expressed as,

$$I_{\mathrm{m}}(x, y) = -\int_0^1 \frac{z(1-z)}{xz^2 - (1+x-y)z + 1} dz. \tag{3.4}$$

Considering masses of ordinary charged leptons are negligible with respect to that of η, i.e., $m_\alpha \ll M_\eta$, the allowed parameter space for the model parameters, M_1, M_η and ξ is obtained from the computed value of $|\mu_{12}|$ from 3.5 keV X-ray line data.[2] The plot showing the variation of the parameters constrained from observed X-ray line data is shown in figure 2. In this plot the ratio (r) of M_η to M_1 is taken to be between 1.0 to 10.0, i.e., $1.0 < M_\eta/M_1 \leq 10.0$. The range of the constrained values of the phase factor, ξ for those mass ratios ($1.0 < r \leq 10.0$) spans from $\sim 10^{-14}$ to $\sim 10^{-8}$. The situation would have been slightly modified if one incorporates the precise values of mixing angles (for example, non-zero θ_{13}). The Yukawa matrix structure is then modified and the phase factor for each flavour α will be different in general. But it can be shown that for such cases the order

[2]The mass of charged lepton is several orders of magnitude smaller than the mass of doublet scalar η which is few hundreds of GeV or more in this framework and hence the ratio, $\frac{m_\alpha}{M_\eta} \ll 1$.

JHEP03(2015)064

of the sum of the phase factors will be almost of similar order that has been obtained in this case. The phase factor determines the co-annihilation of $N_1 - N_2$ and the effective interaction of right-handed neutrino DM with nuclei. However the co-annihilation effect is negligible since the Yukawa coupling and its phase are small enough as shown in figure 2. Thus only possible parameter region for thermally produced dark matter is co-annihilation region with η. For this, the mass degeneracy among the three particles namely, N_1, N_2 and η is very essential in this model framework. Also the result shows the values of phase factor ξ with much smaller orders for the considered mass range than the values needed to produce detectable signatures of direct detection. Hence the DM-nuclei interaction is much lowered from the computed value of ξ constrained by the 3.5 keV X-ray line data. Thus the possibility of direct detection of DM in this framework is suppressed by few orders from the reach of ongoing direct DM search experiments.

4 Summary and conclusion

We have shown that the radiative neutrino mass model can explain the observed 3.5 keV X-ray line signal from the data of various galaxy clusters and Andromeda galaxy (M31). This model can accommodate naturally both neutrino mass and stable cold DM candidate. The small mass difference between the lightest and the second lightest right-handed neutrino has been considered to produce the energy of the X-ray signal. Thus the transition from $N_2 \to N_1 + \gamma$ due to transition magnetic moment via radiative processes involving leptons and charged scalar in internal lines can naturally accommodate all the requirements for the X-ray line signal. The value of the transition magnetic moment (μ_{12}) for such an observed signal is estimated to be few orders of magnitude smaller than the reach of recent DM direct direct detection experimental limits sustaining the possibility of the cold DM candidate in this model to be detected directly. The lifetime of the other process $N_2 \to N_1 + \nu + \bar{\nu}$ is found to be longer than the age of the universe and can be consistent with the transition magnetic moment. But there is strong suppression due to the small mass difference between N_1 and N_2. The other parameters of this model, namely masses of lightest right-handed neutrino (N_1), doublet scalar (η) and phase factor (ξ) between Yukawa couplings, h_1 and h_2 are further constrained from the observed X-ray line data. A very small but non-zero value of the phase difference between Yukawa couplings, h_1 and h_2 has been predicted. Also the co-annihilation between N_1 and N_2 becomes smaller and the s-wave contribution of dark matter annihilation cross-section is calculated to be reduced. Finally the analysis performed here for this model framework would be viable for any DM signal in this energy regime. In addition the DM candidate (lightest right-handed neutrino), being leptophilic and massive, can potentially explain AMS-02 positron excess.

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JHEP03(2015)064

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JHEP03(2015)064